Met.O.751
METEOROLOGICAL OFFICE

the meteorological magazine

NOVEMBER 1964 No 1108 Vol 93
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.751

THE METEOROLOGICAL MAGAZINE

Vol. 93, No. 1108, November 1964

551.582.2(676.1):551.588.2

A LOCAL CLIMATIC STUDY IN TYPICAL DISSECTED TOPOGRAPHY IN THE SOUTHERN REGION OF UGANDA

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Summary.—The kind and magnitude of diurnal local climatic change at Makerere University College Farm are described with the aid of diagrams for two occasions chosen as representing likely extreme weather conditions.

As the topography of the Farm is typical of a large part of the agriculturally important area of south and south-western Uganda similar differences in local climate are likely to be experienced throughout this region.

Introduction.—Makerere University College Farm (latitude 0°28′N, longitude 32°37′E, maximum altitude 3950 feet above M.S.L.) is situated in the southern, lake-shore region (the south and south-west part of Buganda) of Uganda about 11 miles north of Kampala. Originating from a raised peneplain the present topography is highly dissected and characterized by small, often flat-topped hills with the land sloping away to swamps in the valleys; these swamps eventually drain northwards into the Nile system. The amplitude of relief is moderate, with a difference in height between hilltops and valleys of about 300–400 feet which increases somewhat towards the north-west of the region (Singo County), but elsewhere it can be less where pedimentation has been active (Pallister[1]). The vegetation is typically short-grass savanna on the summits and hill slopes, long grass (*Pennisetum purpureum*) and scattered trees on the pediments, with papyrus (*Cyperus papyrus*) a dominant species in many of the swamps; the area is intensively cultivated however (see Plate I). A more detailed summary of the physiography of this region can be found in Radwanski.[2]

During the course of early development at the Farm, a meteorological site was established, and detailed accounts of the weather experienced have been published annually for 1961 onwards (Huxley[3]). This meteorological site is located on top of the ridge running north–south through the middle of the farm, the boundaries of which extend down to the swamps on either side. Although the relative relief is not great, it was obvious that local climatic differences existed, and some measure of the magnitude of these was considered desirable as a preliminary to further investigation on how such variations could affect crop plants and farm animals.

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Methods.—With the limited resources available, it was felt that such a study would best be accomplished by 24-hour surveys along a 'transect' across the Farm from the eastern to the western boundary. The range of elevation experienced was 210 feet (Figure 1). Dry-bulb and wet-bulb temperatures

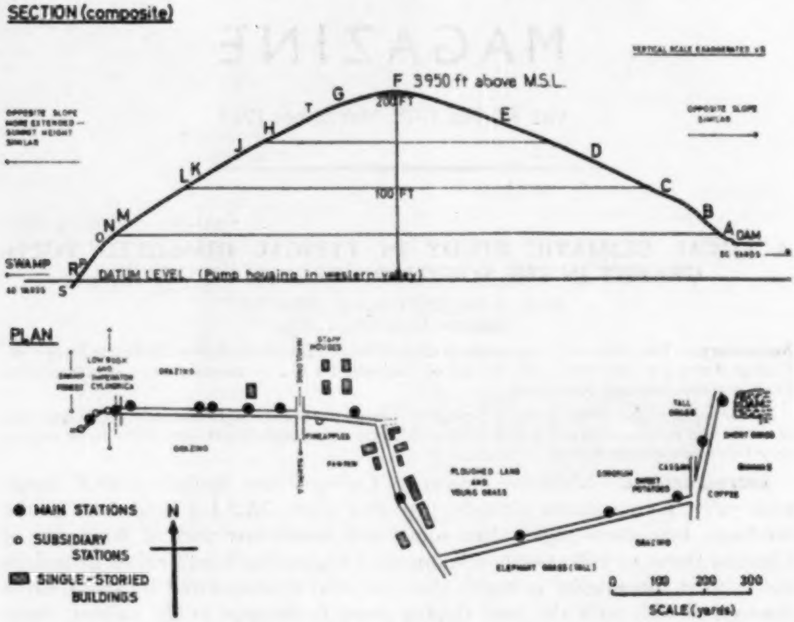


FIGURE 1—PLAN AND COMPOSITE SECTION SHOWING POSITION OF STATIONS AT WHICH RECORDS WERE TAKEN

were measured with a whirling psychrometer at approximately 3 feet above ground level; mean wind speed on the ridge site, wind direction, cloud amount, and dew occurrence were also recorded.

These observations were made during several 24-hour periods of which two have been selected here as representing the possible extremes of local weather conditions. Along the transect, data were obtained successively from not less than 10 stations, which were a few yards to the side of a farm track in most cases. At any one time several psychrometer readings were taken at each station, so as to ensure accuracy, and during daylight hours the psychrometer was shaded from direct solar radiation. Relative humidities and dew-points were calculated using a Mark V Meteorological Office humidity slide-rule. Both cloud amount and mean wind speed were estimated hourly, the latter with the aid of a cup-counter anemometer situated at 2 metres above ground level on top of the ridge. The presence of dew was estimated by examining adjacent short grass and scoring on an arbitrary scale of five degrees.

Results and conclusions.—Figures 2, 3 and 4 show dry-bulb temperatures, relative humidities, and dew-points (as well as the presence of dew) respectively.

Figures 2(*a*), 3(*a*) and 4(*a*) refer to a survey carried out on 8 to 9 December 1960, and Figures 2(*b*), 3(*b*) and 4(*b*) to one on 8 to 9 March 1961. Cloud amounts, wind direction and hourly mean wind speed are shown at the right side of Figures 2(*a*) and (*b*).

(i) *Dry-bulb temperatures.*—

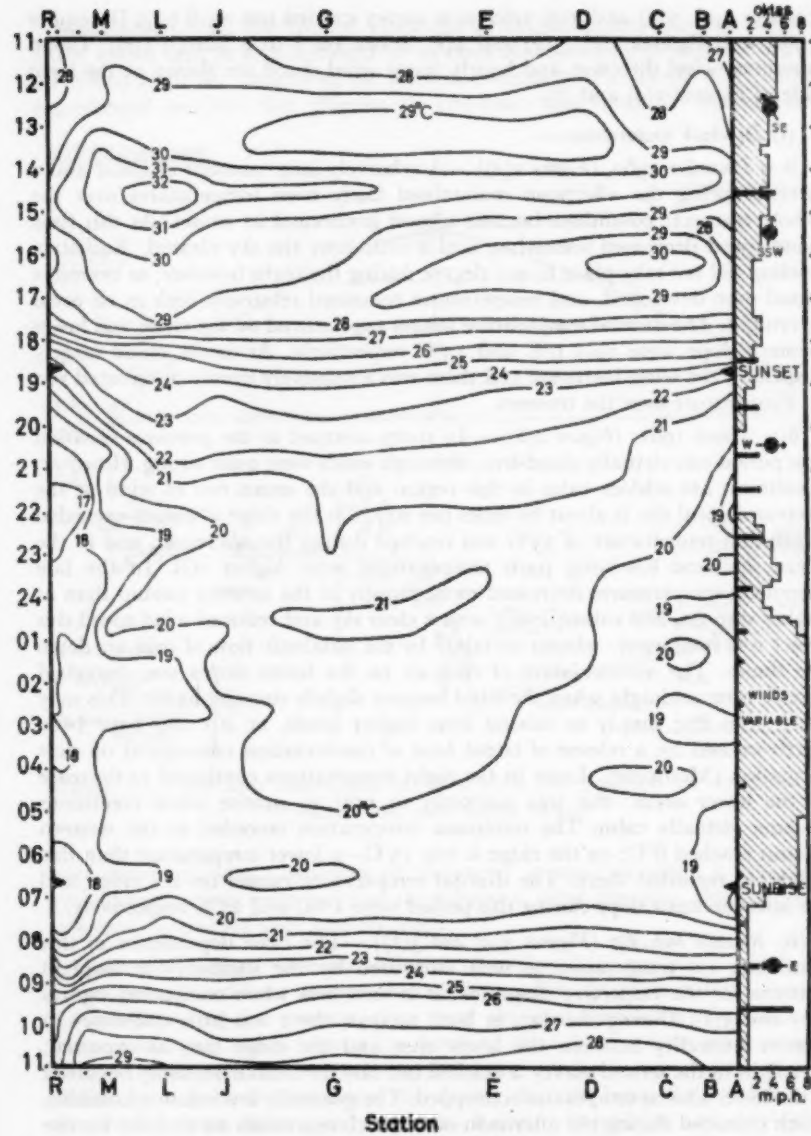
8–9 *December* 1960, (*Figure* 2(*a*)).—A relatively large amount of cloud and a breeze during the afternoon maintained fairly even temperatures over the whole transect; conditions became almost isothermal at sunset. At this time wind speed decreased somewhat, and a little later the sky cleared. Radiative cooling did not take place to any degree during the night however, as extensive cloud soon developed, and temperatures remained relatively high in all areas overnight. The diurnal temperature ranges experienced on the ridge and lower western slope were only 9°C and 13°C respectively. At dawn, cloud largely dispersed, the wind increased and there was a relatively evenly distributed rise in temperature over the transect.

8–9 *March* 1961, (*Figure* 2(*b*)).—In sharp contrast to the previous occasion this period was virtually cloud-free, although winds were quite strong. However, conditions are seldom calm in this region and the mean run of wind at the meteorological site is about 60 miles per day. On the ridge a seldom-exceeded maximum temperature of 33°C was reached during the afternoon, and in the more sheltered low-lying parts temperatures were higher still. In the late afternoon temperatures decreased more rapidly in the western swamp than at higher stations, and subsequently with a clear sky and reduced wind speed this effect was reinforced—almost certainly by the katabatic flow of cold air down the slopes. The accumulation of cool air on the lower slopes was disturbed shortly after midnight when the wind became slightly stronger again. This may have been due simply to mixing from higher levels, or it could have been partly caused by a release of latent heat of condensation consequent on dew formation (Monteith[4]). Later in the night temperatures continued to decrease in the lower areas; this was markedly so near to sunrise when conditions became virtually calm. The minimum temperature recorded in the western swamp reached 8°C; on the ridge it was 15°C—a lower temperature than this is seldom recorded there. The diurnal temperature ranges on the ridge and the lower western slope during this period were 17°C and 27°C respectively.

(ii) *Relative humidity* (*Figures* 3(*a*) *and* 3(*b*)).—The close dependence of this parameter on temperature is well illustrated by the similarity in isopleth patterns for the respective diagrams; it is seen best when comparing figures 2(*b*) and 3(*b*). During the day, in both surveys, there was little difference in relative humidity between the lower sites and the ridge but, as expected, overnight in the second survey a marked increase in relative humidity occurred at the lower sites as temperatures dropped. The generally low relative humidity which occurred during the afternoon of 8 March represents an extreme for the locality.

(iii) *Dew-points and the presence of dew.*—

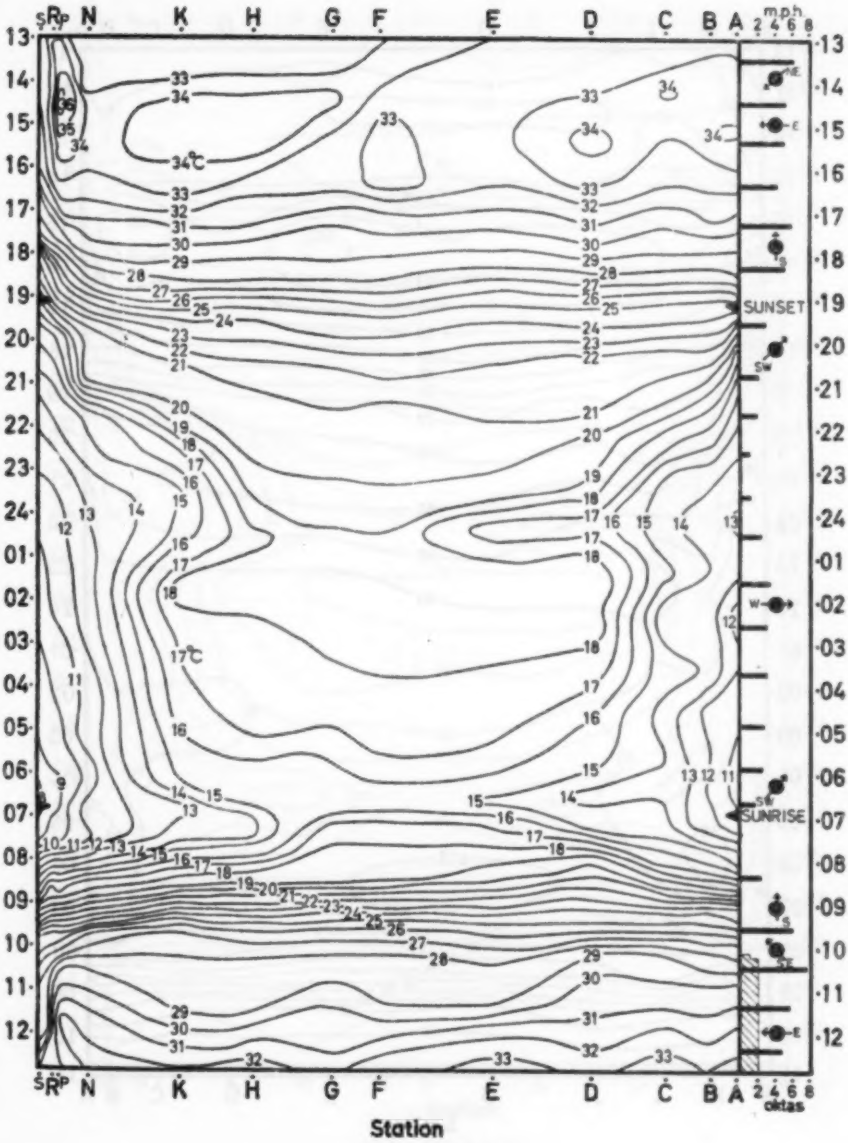
8–9 *December* 1960 (*Figure* 4(*a*)).—The variation between dew-points over the whole area was not more than 2.5°C at any one time. A slight rise commencing in the afternoon continued until about 0300 hours (note: all times are East African Standard Time, i.e. GMT + 3 hours) and examination of the



(a) 8–9 December 1960

FIGURE 2—CHANGES IN DRY-BULB TEMPERATURE ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

Local times are shown against the vertical axis; cloud amounts are shown by hatching; wind speeds are shown by bars and the major changes in direction by arrows. Stations at which records were taken are shown in Figure 1.



(*b*) 8–9 March 1961

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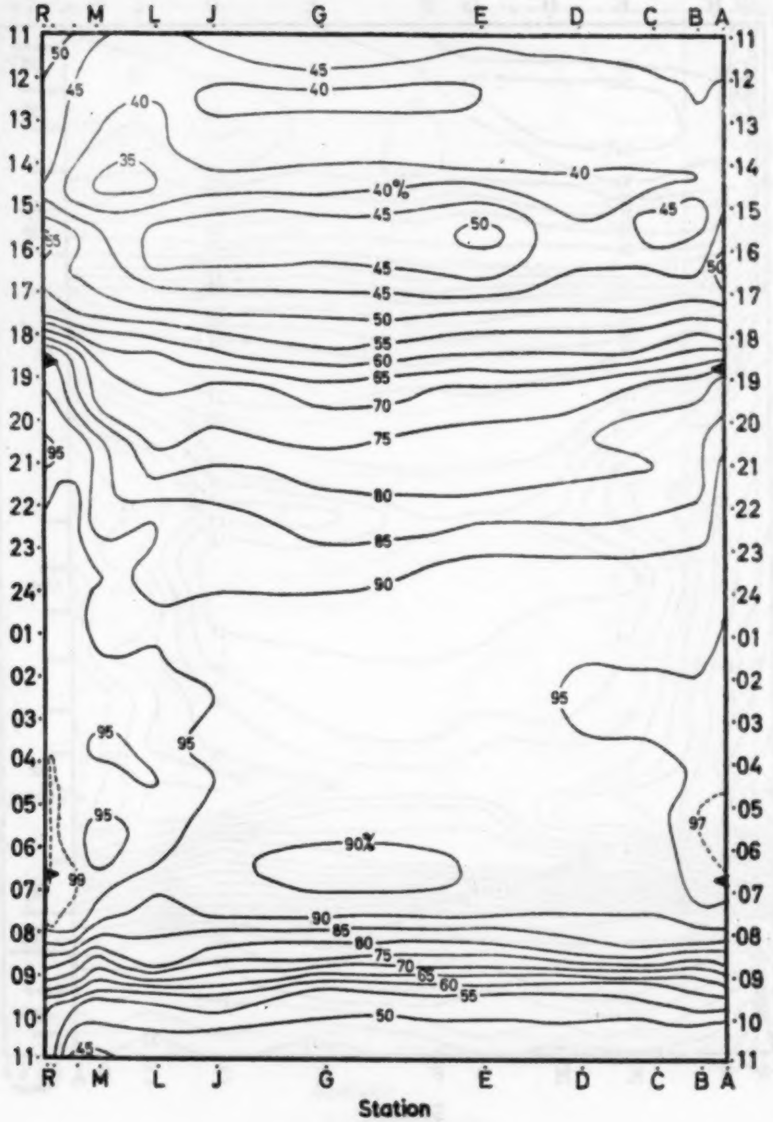
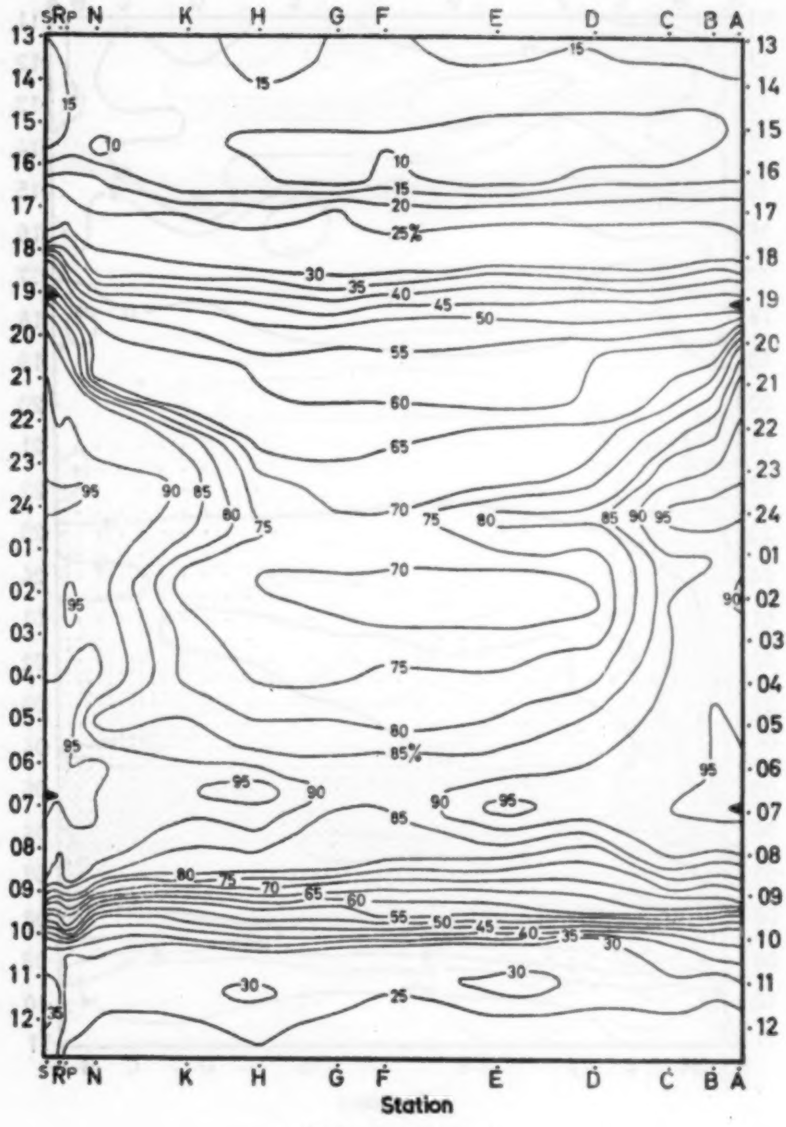


(*a*) 8–9 December 1960

FIGURE 3—CHANGES IN RELATIVE HUMIDITY ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

Stations at which records were taken are shown in Figure 1.



(*b*) 8–9 March 1961

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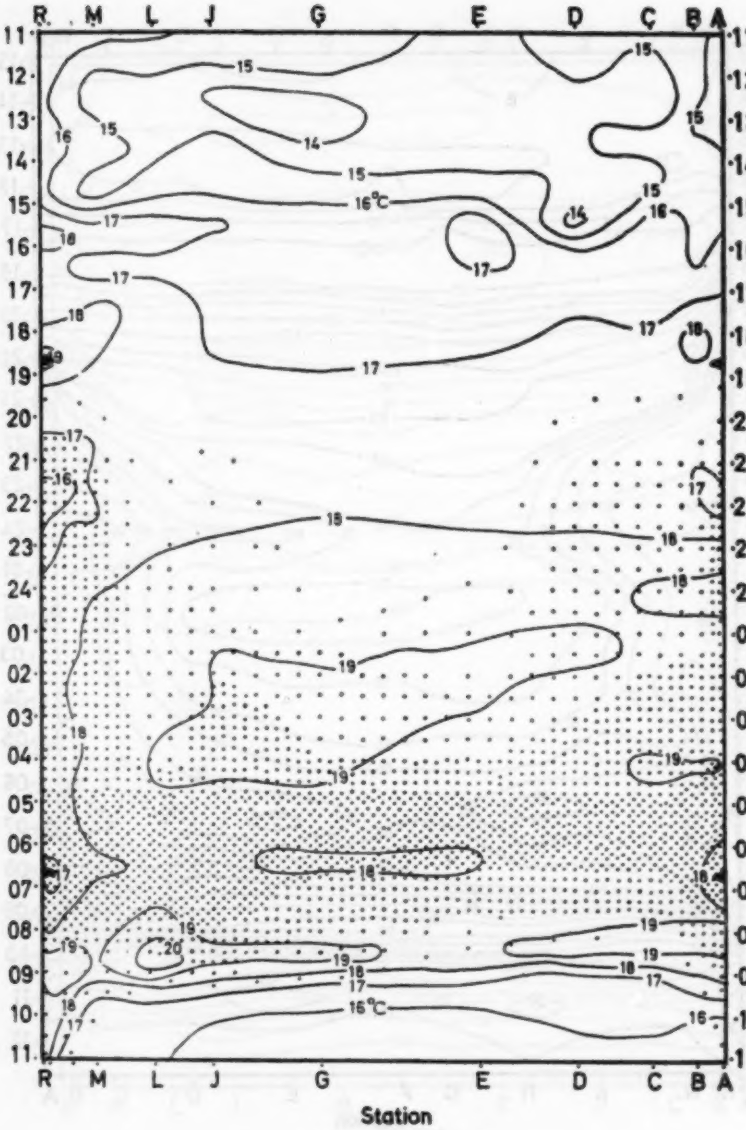
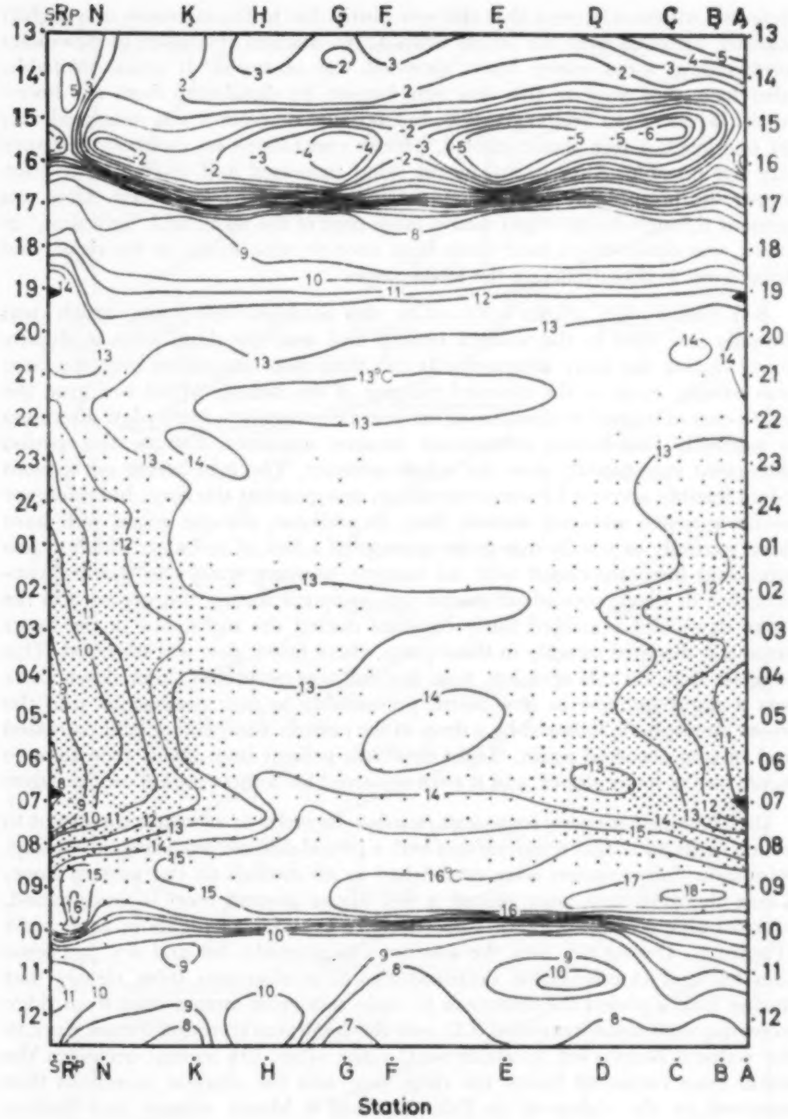


(*a*) 8–9 December 1960

FIGURE 4—CHANGES IN DEW-POINT ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

The occurrence of dew on short grass was also recorded on an arbitrary scale of five degrees, i.e. nil, trace, light, medium and heavy. The last four degrees are represented on the diagram by an increasing number of dots. Stations at which records were taken are shown in Figure 1.



(*b*) 8–9 March 1961

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synoptic situation showed that this was partly due to the incursion of a slightly moister air mass over the whole district. No marked reduction in dew-point occurred in areas where heavy dew-fall was observed. It seems probable, therefore, that most of this dew was formed by distillation from the lower, moist layers of soil and vegetation, but because dew-point was measured only at one level, 3 feet above ground, precise conclusions on moisture exchange are not possible. After dawn, as the wind increased and mixing with drier, upper air presumably took place, dew-points dropped somewhat. Dew was present throughout the night over a large part of the farm, and 'light dew,' or more, was observed on short grass from 0200 to 0800 hours on the ridge, and from 2100 to 0800 hours on the lower slopes.

8–9 *March* 1961, (*Figure* 4(*b*)).—On this occasion dew-point, which was initially low even in the western swamp and near the dam, became slightly lower during the early afternoon. At this time most vegetation over the farm was wilting, even on the elevated margins of the swamp. Wind was from the north-east as is usual at this time of the year (Henderson[5]), but by late afternoon a southerly lake-breeze component became apparent. During this period dew-point rose rapidly over the whole transect. The lake-breeze component could feasibly account for some increase in dew-point at this time, but reference to the synoptic situation showed that, in addition, the rise might well have been partially or wholly due to the passage of a belt of moist air which at one time had been associated with an easterly pressure wave. No marked convergence or divergence of air masses was apparent during this period. On the ridge dew-point remained fairly constant during the night, but in the lower regions it dropped steadily in those parts where heavy dew was observed. This suggests that, on this occasion, true dew-fall was occurring. After dawn there was a slight increase in dew-point, presumably as dew evaporated into the lower atmosphere, followed by a drop as the easterly wind component increased and mixing occurred again. 'Light dew' was present from about 2200 to 0930 hours on the lower slopes, and it even occurred for a short period on the ridge.

(iv) *Additional minimum temperature records.*—In order to ascertain the extent to which night minimum temperatures over a period differed from ridge to swamp, minimum thermometers were established at six stations on the western slope. These thermometers were placed 3 feet above ground level in open-ended, asbestos-pipe screens (Lake[6]). Records were kept for 24 nights in early 1961 (Figure 5). During this time the weather was generally hot and dry, but some rain fell and cloudy nights occurred also. The diagrams show clearly that during such a period the difference in night minimum temperature from ridge to swamp commonly exceeded 6°C, and the minimum screened temperature in the western swamp fell to about 10°C quite often. On several occasions the warm zone remained below the ridge top, and the marked inversions that occurred on the nights of 22 February and 6 March suggest that distinct stratification of the air can occur, as has been reported elsewhere (Weise[7]).

Discussion.—The topography of the site on which these observations were made is similar to that experienced over a large part of the south and south-west of Uganda. Elsewhere in this region relative relief may be somewhat greater, and the exposure different, but the surveys reported here are likely to indicate the kind and approximate magnitude of local climatic changes which may be expected under similar weather conditions. It is clear that the variations in

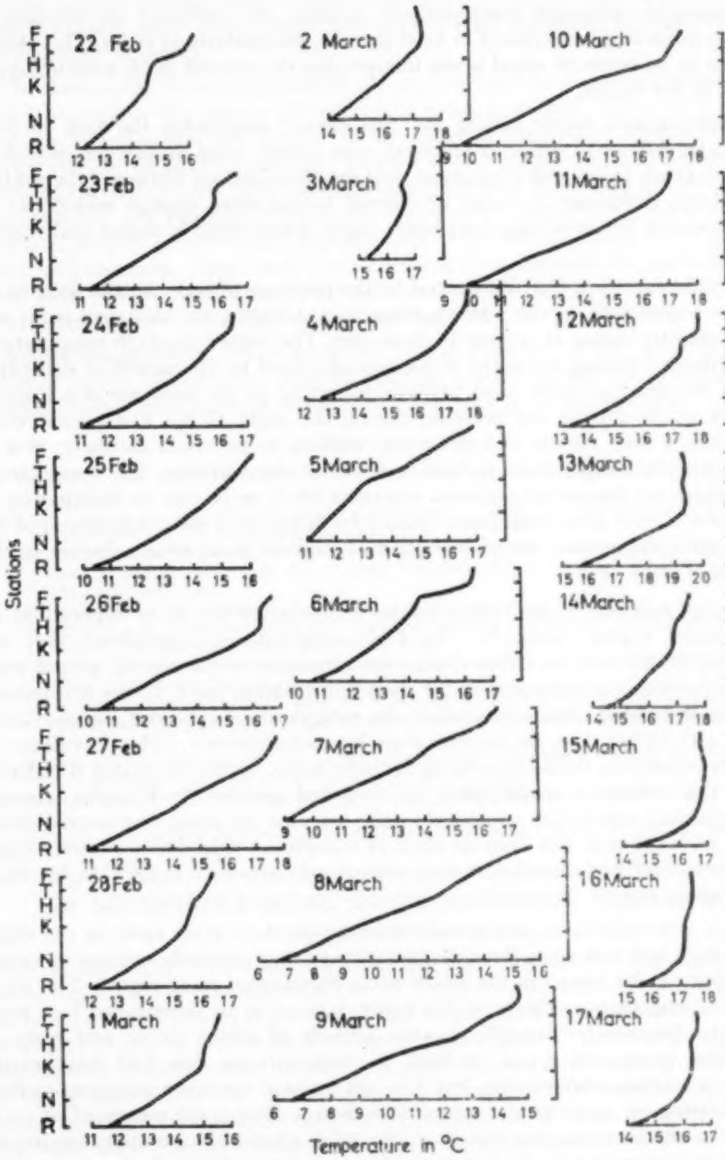

FIGURE 5—SCREENED NIGHT-MINIMUM TEMPERATURES AT A HEIGHT OF 3 FEET AT SIX STATIONS ON THE WESTERN SLOPE DURING EARLY 1961

Stations at which records were taken are shown in Figure 1 and were at the following heights above the datum line: F, 205 feet; T, 175 feet; H, 150 feet; K, 108 feet; N, 48 feet; R, 0 feet.

Stations at which records were taken are shown in Figure 1.

topography, although comparatively modest, are sufficient on occasion to cause quite large differences in local climate, particularly at night. This clearly needs to be borne in mind when interpreting the records from meteorological sites in the region.

Observations taken during the first survey emphasize the lack of local climatic difference which is apparent over varied relief during the periods in which much cloud and wind occur, but the most striking feature of the study is the large difference in range of diurnal temperature change which can be experienced between ridge and lower slopes when cloud is absent and wind is light.

Conditions were little influenced by the presence of water in the dam or by dense vegetation in the western swamp, and during the day dew-point was only slightly higher at or near to these sites. The higher dry-bulb temperatures experienced during the night of the second period in the eastern as compared with the western valley were unlikely to be due to the presence of a body of water in the former site because, during the night of the first period when conditions were cloudy and there was unlikely to be much katabatic flow of cold air, the temperatures in both valleys remained similar. The temperature difference on the second occasion was more likely to be due to dissimilarity in the rate of cold air accumulation caused by disparity in elevation, extent of the respective slopes, and the contribution of cold air from areas adjacent to the Farm (Figure 1).

Aspect had only a small effect on day temperature as is to be expected in an equatorial region (Geiger[8]). The high temperatures experienced near the bottom of the western valley during the afternoon of the second period were almost certainly attributable to the sheltered situation there. In the first period, during somewhat cloudy conditions, the western slope achieved a temperature only 2°C higher than the eastern slope by mid-afternoon. The prevalence of windy conditions throughout most daylight hours at this site makes it unlikely that this difference would often be exceeded greatly. At Kiambu, Kenya, Kirkpatrick[9] noted that an easterly slope warmed up about one hour quicker than level ground, but even on days of continuous sunshine a westerly slope of gradient 20° had a maximum temperature only about 2.0 to 2.5°C higher than an easterly one.

Dew is invariably recorded each morning on short grass even on the ridge (Huxley[3]) and it is clear from the two surveys that relatively copious amounts are likely to be found in the lower areas throughout most nights. The agricultural importance of dew in this region has yet to be determined but, even though climatically 'humid', seasonal periods of aridity occur and rates of potential transpiration can be high. In both surveys, dew had disappeared some two hours after sunrise, but it is not unusual on other occasions to find it persisting on crops until 1000 or 1100 hours. Dew-point measured at 0900 hours in the thermometer screen on the ridge almost always approximates to the recorded minimum temperature, hence it seems likely that a proportion of the observed dew may often be true dew-fall. The results of the second survey provide evidence that this was certainly so in the lower areas on that occasion. The contribution which true dew-fall can add, in quantitative terms, to the water balance can only be slight (Slatyer and McIlroy[10]) and in this respect it is probably of small importance except in arid regions. Nevertheless, even

elsewhere, dew may well have a significant effect on crop growth, as it restores plant turgidity early in the night and it can delay the onset of water stress the following morning.

The lower-lying areas in this region are not preferred for domestic settlement, partly because of the greater prevalence of mosquitoes and other insect pests near the swamps, but also because of the physical discomfort engendered by the greater extremes of temperature and the higher relative humidities experienced as compared with more elevated sites. With the likelihood of increasing land pressure and the need for greater agricultural productivity, lower areas, which at present remain either unproductive or unused, are likely to be developed agriculturally. Thus there is now a need to investigate the influence of these local climatic variations on the growth and yield of crops, the prevalence of pests and diseases, and the comfort and behaviour of farm animals.

Acknowledgement.—The assistance of the Director of the East African Meteorological Department and his staff in providing and interpreting information about the synoptic meteorology is gratefully acknowledged.

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551.5(09):551.507.352

202 METEOROLOGICAL RECONNAISSANCE SQUADRON

By R. F. M. HAY, M.A.

The disbandment of No. 202 Meteorological Reconnaissance Squadron ends more than two memorable decades of intimate and valuable co-operation between an operational squadron of the Royal Air Force and staff of many branches of the Meteorological Office. Over the past 18 years this Squadron has made over 4000 sorties with great regularity, entailing nearly 40,000 hours of flying mostly over the open oceans. On a number of occasions it has been given publicity by the Press and by television, and as recently as May 1964 the BBC ran a Northern Ireland schools' radio programme on the work of the Meteorological Office and of 202 Squadron.

A brief mention of the history of the Squadron before its formal association with the work of the Meteorological Office began in the Second World War, is not out of place here, since it forms a worthy prelude to the events to be described. The formation of the Squadron dates back to October 1914, when it

began its operational life as No. 2 Squadron Royal Naval Air Service at Eastchurch flying 70-hp Short Biplanes. Photographic reconnaissance for the historic Zeebrugge raid was among its achievements in the First World War. The Squadron was disbanded in 1921; however within a few years (1 June 1929) No. 481 (Coastal Reconnaissance) Flight in Malta was redesignated as No. 202 Squadron. In September 1939 the Squadron was moved to Gibraltar (flying Catalinas and Sunderlands) and in the next five years was credited with the sinking of three enemy submarines and with a share in sinking or damaging three others. It was also a Catalina of No. 202 Squadron which picked up General Mark Clark from a submarine after his clandestine visit to Algiers to meet French Resistance leaders.

Meteorological flights have continued to provide synoptic observations of the highest quality and intrinsic value for weather forecasting and other scientific purposes over many years. So today some effort is required to recall the grim situation which obtained quite early in the second war, when the enemy's tactical successes effectively denied vital meteorological information over immense areas of land and ocean to our national meteorological services; and so made the provision of air meteorological reconnaissance indispensable. Early in 1939 the Meteorological Office was looking for means of obtaining weather information at sea to replace ships' reports, always liable to be completely suppressed in war, and concluded that the best arrangement would be to have its own special flights for that purpose. However the shortage of operational aircraft delayed developments until late in 1940, when three flights using Blenheim III aircraft were established within Coastal Command, at Bircham Newton, St. Eval and Aldergrove. During the remaining years of the war these flights were successively re-equipped with Hudson, Hampden, Ventura and Halifax aircraft, the last named being the standard aircraft for meteorological reconnaissance squadrons by the end of the war. In the same period, ranges of 200 miles with the Blenheim aircraft were extended up to 900 nautical miles, aircraft establishments were increased on some flights to provide for two sorties daily, and additional flights were operated from airfields as far apart as Bircham Newton, Brawdy, Tiree, Wick, Reykjavik, the Azores and Gibraltar. This effort was not achieved without many setbacks due to mechanical troubles and shortage of aircraft, which were overcome with the aid of Coastal Command and later the United States Army Air Force, both of which lent aircraft of their squadrons to the meteorological flights.

A Meteorological Air Observer Section of the Royal Air Force (General Duties Branch) was formed in September 1942, and had achieved a fine record of active service by the end of the war. It was recruited from experienced staff of the Meteorological Office who were then trained in making observations from aircraft. Officers were posted to meteorological flights in June 1943, and non-commissioned officers (NCO's) followed not long afterwards. Since 1948 the section has been staffed by volunteer Scientific Assistants. Over a long period, occasions when a member completed 400 sorties have been marked by a celebration within the Squadron. Master Pilot F. Radina and Master Signaller J. Stratton were among those who achieved this target, while during his several tours of duty with the Squadron the present Flight Commander, Flight Lieutenant Ignatowski, AFC, DFM, had logged 397 sorties by the date of the Squadron's disbandment and received a L. G. Groves Memorial Award in 1963. In a short account few individual names can be included, and a

mention of four Air Meteorological Observer Leaders, Flight Lieutenant Cayhill, Flight Lieutenant Parsons, Flight Sergeant McCubbin and Flight Sergeant Hunt, implies that there were many others who also performed their duties with outstanding success and contributed in no small measure to the fine performance and high morale of the Squadron as a whole. Flight Sergeant Hunt was also a recipient of a L. G. Groves Memorial Award in 1959.

Flight plans of the reconnaissance squadrons were gradually extended until the existing triangular tracks were devised in which the first and third legs were flown at a low level (950 mb) and the second leg at a higher level (500 mb). Routine eye and instrument observations were made every 50 miles on the flights, besides observations of wind by multiple drift, and sea-level pressure was determined at every 200 miles on the low-level legs and at the positions of the soundings to 500 mb. Determination of sea-level pressure involved descent to about 50 feet estimated above the sea surface in the early days, but after radio altimeters were fitted to the aircraft, a descent to about 200 feet only above the sea surface was required.

Towards the end of the war No. 202 Squadron performed anti-submarine duties at Castle Archdale in Northern Ireland, prior to being disbanded for a few months during 1946 and then being redesignated as a meteorological reconnaissance squadron at Aldergrove. Halifax aircraft continued to be used for several years and during this period 32 crew members lost their lives in aircraft accidents. This toll of life exacted in peacetime, in the pursuit of weather observations from potential or actual storm areas at the meteorologists' request, demanas recall and grateful mention here. The Squadron was re-equipped with Hastings aircraft in 1950, and the fact that these aircraft have been used ever since that date with no further loss of life is some tribute to the flying crews and to the suitability of the aircraft for this exacting task. Soon after the end of the war all the meteorological reconnaissance flights were disbanded with the exception of those from St. Eval ('Epicure'), Gibraltar ('Nocturnal') and Aldergrove ('Bismuth'), and after about 1950, No. 202 Squadron was left as the sole long-distance 'met recce' flight from a base in the British Isles.

During the last few years the Squadron had an establishment of five Hastings and their crews comprised captain, 2nd pilot, navigator, engineer, two signallers and two air meteorological observers. Sorties were made on five days a week on standard Bismuth tracks extending some 800 miles over the Atlantic, and ranged from the Biscay area through the Western Approaches to Icelandic waters. Choice of track to be followed was made by the forecasting staff at Headquarters, Bracknell, and was normally dictated by the need to cover an area where information was sparse or missing, or where confirmation or otherwise of bad weather or new developments was required. The flights were most often made into the worst possible weather conditions, and the regularity with which tasks were completed has always been a source of pride to the Squadron. With a view to reducing this bad weather hazard some of the Hastings were recently fitted with cloud collision radars, and the operational value of this equipment, apart from some teething troubles, had been clearly demonstrated by the time of the Squadron's disbandment.

The information provided over the years by the Bismuth flight of No. 202 Squadron has undoubtedly been of very great value for military and civil aviation interests at all times, and for operational forecasting for the general

public on certain occasions. A striking instance was provided by Mr. E. Gold, F.R.S., in his Symons Memorial Lecture delivered before the Royal Meteorological Society in April 1947, when he cited a meteorological reconnaissance made during the night of 7–8 January 1947, which, by penetrating close to the centre and there making an ascent to 500 mb, gave a detailed synoptic picture of one of the deepest Atlantic depressions for several years. On this occasion the meteorological observer was the son of a previous Symons Lecturer, Mr. F. Entwistle, and Gold added "I have included this chart because I regard this flight as one of the most notable achievements in meteorological observations and worthy of a high place in meteorological literature." Another important occasion was on 24 September 1957 when a Bismuth aircraft flew through the centre of hurricane CARRIE, the hurricane which had caused the loss of the sailing ship *Pamir* a short time earlier. Flight Lieutenant Dinnes, who was the captain of this aircraft, vividly recalled this occasion to the writer recently. Torrential rain and severe turbulence were encountered throughout the flight, and the aircraft captain's description makes it evident that he found the eye of the storm still in existence, and penetrated it in a position approximately 51°30′N, 14°00′W, that is about 150 miles to the west-south-west of Ireland. He then flew within the eye for some time where he found the usual features of light winds and little cloud, apart from a few cumulus, with a characteristic surrounding amphitheatre of cloud extending to a great height. This flight was a normal sortie made on the standard track 'Bravo' at the request of the Central Forecasting Office, then at Dunstable.

Besides affording support for the forecasting services through so many years, the Bismuth meteorological reconnaissance aircraft have also acted on numerous occasions as a mobile aerial platform for experimental work by other government departments, notably the Atomic Energy Authority. Since 1948 each flight has sampled the air for radio-active dust, using a cylindrical filter of high collective efficiency carried on the aircraft. A representative sample of the dust content of the lower troposphere was thereby obtained, and at the end of each flight the filter with its collected dust was sent for analysis to the authority for whom the sampling programme was carried out. In this way the Squadron assisted the aim of measuring concentrations of radioactivity at various levels around the British Isles which, being situated far from test sites, form a suitable observation area for the study of contamination on a global scale. The aircraft observations therefore rank among the most important contributions to this problem, and the results were used in an American as well as a British report on the subject. The second series of nuclear weapon tests held at Christmas Island in 1958 afford another example of invaluable support given by personnel of 202 Squadron, as it were behind the scenes. On this occasion one officer and four NCO's from the cadre of air meteorological observers at Aldergrove were detached to Christmas Island. There they flew numerous sorties in aircraft of Shackleton and Canberra squadrons, and provided upper wind observations and cloud photographs over a large operational area. The procedures used in making and transmitting observations to base were similar to those used on normal sorties made by 202 Squadron from Aldergrove.

In this article an attempt has been made to place on record in a meteorological journal the remarkable achievements of this Squadron in the task of weather observing. While it may be premature to speculate on the effects to

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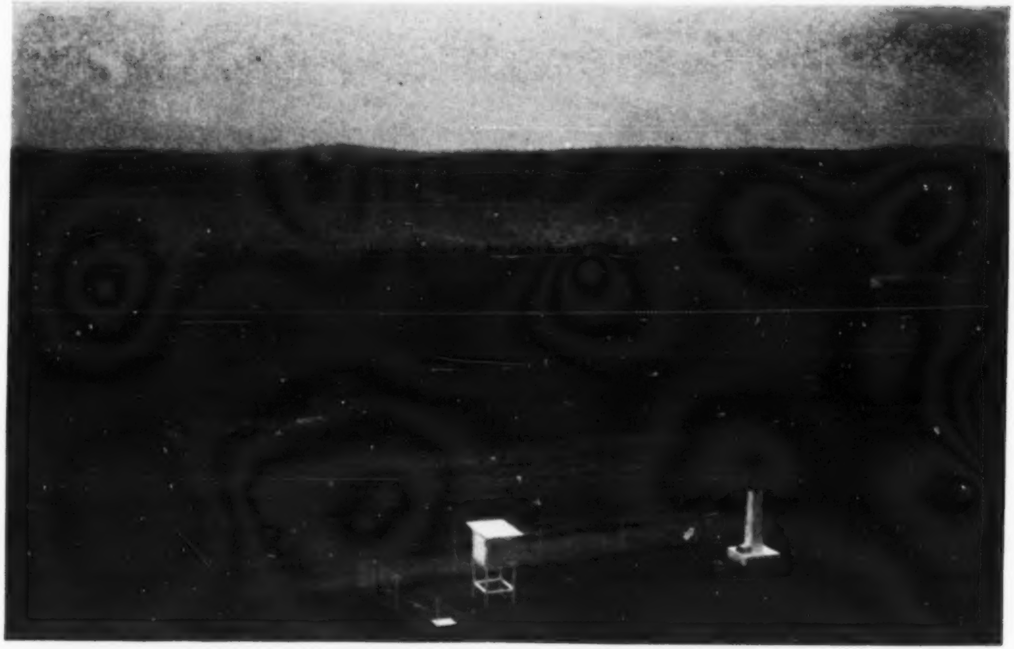

Photograph by P. A. Huxley

PLATE I—VIEW WESTWARDS FROM THE TOP OF KABANYOLO FARM RIDGE SHOWING TYPICAL DISSECTED TOPOGRAPHY

(See page 321.)

Crown copyright

PLATE II—THE 16-FT DIAMETER AERIAL OF THE 8.6-MM RADAR AT THE ROYAL RADAR ESTABLISHMENT, MALVERN

(See page 337.)

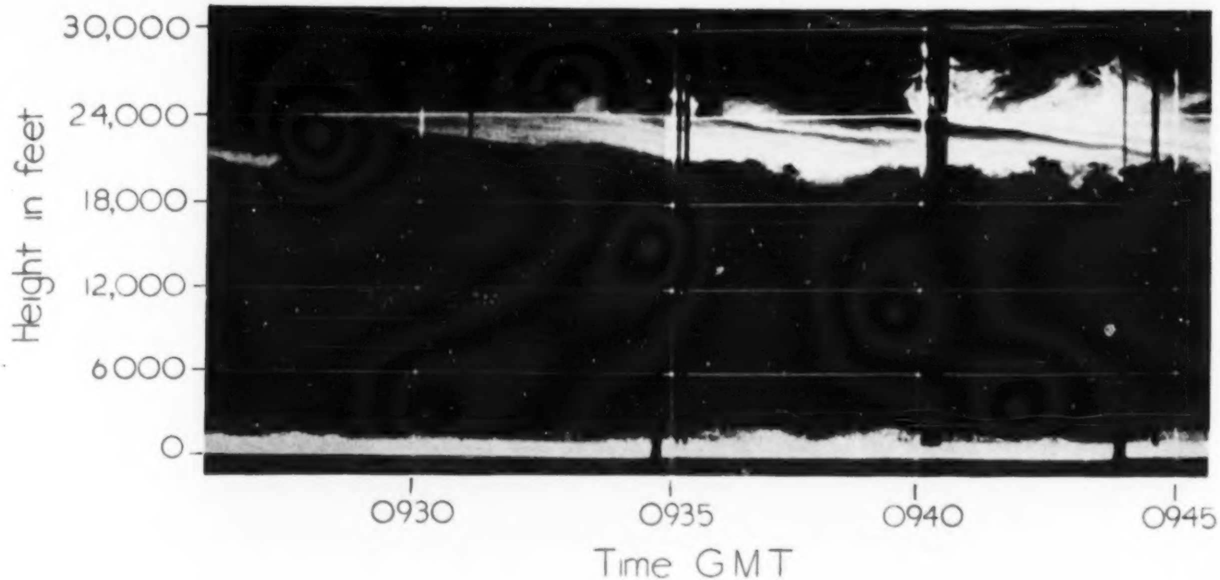

PLATE III—AN EXAMPLE OF A HEIGHT–TIME RECORD FROM THE 8.6-MM RADAR ON 24 SEPTEMBER 1962, WITH ECHO BETWEEN 18,000 AND 30,000 FEET

The cloud was reported as 7/8 cirrus fibratus at first, but with cirrostratus predominating at 0945 GMT. There is clear evidence of fallstreaks in the echo (see page 340). At 0940 and 0945 2/8 to 3/8 of stratocumulus with its base estimated as 2000 ft passed through the zenith but was not detected by the radar. The vertical white lines are electronic time markers. The vertical black bands are caused by intensity measurement. The band of echo at the bottom of the record is the transmitter pulse, which prevents observation of the first 1000 ft. The spots of echo just above this are 'angels', probably the detection of insects passing through the radar beam.

To face p. 337

PLATE IV—MEMBERS OF 202 METEOROLOGICAL RECONNAISSANCE SQUADRON, ALDERGROVE, IN THE SUMMER OF 1964

Back row, left to right: Sergeants B. G. Young, J. M. Malcolm, M. W. P. Pain, A. A. J. Higgins, I. E. Stephenson.

Front row, left to right: Seargeants R. E. Bywater, C. A. Brimacombe, D. W. M. Smithson, F. Garlick, B. Morris. 202 Squadron was disbanded on 31 July 1964. (See page 333.)

the community at large of losing the services of 202 Squadron, it will certainly be felt most severely by those responsible for forecasting weather at low levels over the oceans around this country. Over the years the Squadron performed an outstanding service to meteorology, fulfilling a requirement for on-the-spot observations from remote areas at short notice, with a promptness and flexibility that cannot be rivalled. The splendid reputation which it enjoyed throughout the Meteorological Office pays tribute to the fine spirit of co-operation of the aircrews and their devotion to duty. (See Plate IV).

551.501.81:551.508.85:551.576.2

CLOUD DETECTION WITH 8.6-MILLIMETRE WAVELENGTH RADAR

By W. G. HARPER, M.Sc.

Summary.—From an assessment with an 8.6-mm radar at Malvern it is concluded that about 50 per cent of high and low clouds, and 75 per cent of medium clouds in southern England give detectable echoes, provided that the equipment is maintained at high sensitivity. The small pulse-volume of the Malvern radar gives great detail in the echo patterns. It reveals fallstreaks, suggesting the presence of precipitation-sized particles, in a substantial proportion of the echoes, particularly at high and medium levels. It is concluded that 8.6-mm radar is often unreliable as an indicator of true cloud bases and tops. Some dense water fogs have given weak echoes, but the fog tops could not be defined. The effects of attenuation at 8.6-mm wavelength are discussed.

Introduction.—The move of the Meteorological Office Radar Unit from East Hill to Malvern in 1959 at the invitation of the Royal Radar Establishment made possible a series of meteorological measurements with specialized radar equipments.[1] These included a radar especially designed for use at millimetric wavelengths. Its special feature is its accurately contoured parabolic aerial 16 feet (4.9 m) in diameter (Plate II). At 8.6-mm wavelength this gives a radar beam only 8 minutes of arc in width to half-power points, making it suitable for a variety of meteorological studies. Since, apart from a short series of measurements at 8.6 mm by Roberts,[2] and an assessment of attenuation at 8.6 mm by Robinson,[3] no meteorological measurements at a wavelength shorter than 3 cm had been made in this country, the first use to which the radar was put was an assessment of the detectability of various cloud systems. The results are summarized in this paper, and the effects of attenuation are briefly discussed. Studies of selected radar records illustrating the exceptional resolution given by this radar in cloud detection will be published elsewhere, as will a further use of 8.6-mm radar, namely the measurement of rainfall, along an extended line, from the attenuation of the radar beam.

Equipment and recording.—Detailed comparison between visual and radar records was commenced in April 1961, on completion of the initial working-up of the equipment, and continued until October 1962. The radar was operated pointing vertically, to ensure that ranges of detection and the resolvable volume were as small as possible. At a height of 3 km the resolvable volume was 1100 m^3, which by normal radar standards is exceptionally close resolution. Signals were displayed on a cathode-ray tube as an intensity-modulated display linear in height. By photographing this and applying a slow lateral displacement to the trace a height–time pattern of the precipitation passing overhead is built up, to which electronic height and time markers are added. Ten minutes' record was photographed on each 35-mm frame. The echo patterns have equal scales in the horizontal and vertical on this record if the cloud systems are moving through the beam with a wind speed of 36 knots. A range-amplitude display is available for intensity and calibration measurements.

To record cloud conditions a Wide-Angle Target Camera type GW1 was installed as a sky camera, with automatic photography at 5-minute intervals, the shutter being triggered by the same circuit which provided time marks on the radar records. The angle of acceptance of the camera was 140 degrees, and it was usually tilted to bring in the horizon on a chosen azimuth as an aid to identification. The sky camera could not be used in precipitation or in poor light, and as a routine its records were supplemented by conventional meteorological observations of clouds and weather at intervals of 5 or 10 minutes and by the observer's estimates of cloud types affecting the zenith. Experience showed that the observer, with his ability to judge the angular velocity of clouds near the zenith, can determine cloud types of significance to the radar more efficiently than is possible even from 5-minute sky photographs. Much of the material was accumulated in the form of hourly runs. Analysis of 'occurrences' of detection and non-detection of cloud has been mainly from mounted prints from the radar height–time recorder and the sky camera, annotated with the observer's reports, and mainly for 5-minute intervals.

Much record had to be discarded from the comparison when the cloud, even though substantial in total amount, was not affecting the zenith. A further cause for discarding record has been that it was not felt possible to claim detection or non-detection of a low-cloud layer, e.g. stratus, when rain was falling through it from a medium-cloud layer above, for then precipitation echo blanketed the layer from which echo from the stratus cloud itself might have been detected; nor has it usually been possible in this case to claim detection of medium cloud either, for the low cloud usually prevented visual observation of the middle-level and high-level clouds present. Exclusion was the only possible course if the cloud type was not reported visually, since otherwise it would have biased the analysis towards detection.

Calibration of the radar.—The radar has been calibrated both against a standard metal sphere and against raindrop distributions measured with filter papers in steady light rain. The measured intensities in both cases were slightly lower than the theoretical values,[4] in the sphere experiments by an average of about 1 dB,* in the filter paper comparisons by about 4 dB. The agreement however was sufficiently good to allow the adoption of the calculated level of 'best' performance of the radar. Neither method of calibration could be made daily, but it was possible to take account of short-term fluctuations in radar performance, e.g. those due to deterioration of valves and circuit components, by making regular measurements of the echo intensity from a ground target which has shown unusual stability. These measurements were made before and after each hourly run, or as soon as precipitation had ceased, and have proved a reliable guide to radar performance.

The present analysis includes all records made with radar performance up to 5 dB below its optimum as a compromise to obtain sufficient material. Five dB corresponds to a factor of 3 in radar reflectivity of precipitation targets, or to a factor of about 1.7 in height of detection. Thus an echo from altocumulus just detectable at 8000 ft with performance at its optimum would not be detectable above 4500 ft if the radar sensitivity had fallen by 5 dB.

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*It is usual to express radar intensity ratios on a logarithmic scale. The ratio of two signal intensities P and Q is given in decibels (dB) by $10 \log_{10}(P/Q)$.

Analysis.—The result of an initial analysis of these records is given in Table I(*a*), with division of cloud types into genera according to the international cloud classification. The only exception to this has been the separation of cumulus humilis, cumulus mediocris and cumulus congestus because of their major differences in vertical development. It will be noted that stratus has been excluded from the table. This is because it was almost always reported either in conjunction with stratocumulus, without separate identification of amounts (it was then included as an entry under Sc) or as stratus fractus beneath precipitating altostratus or nimbostratus, when it was excluded because of the possibility of confusion with echo from rain falling through the stratus layer. At line 1 of the table are given the numbers of observations of each cloud type, at line 2 the numbers in which echo appeared to be associated directly with this cloud, and at line 3 the percentages of detection that these represent.

TABLE I—ANALYSIS OF DETECTION OF CLOUD TYPES WITH 8.6-MILLIMETRE RADAR (*a*) FOR INDIVIDUAL CLOUD TYPES, AND (*b*) GROUPED AS HIGH, MEDIUM AND LOW CLOUD

(*a*) Cloud type	Ci	Cc	Cs	Ac	As	Ns	Sc	Cu hum	Cu med	Cu con	Cb
Number of observations	121	2	32	250	178	34	286	149	219	40	0
Number with echo	46	0	29	169	148	34	178	9	125	40	—
Percentage detected	38	0	91	68	83	100	62	6	57	100	—

(*b*) Cloud types	High Ci, Cs	Medium Ac, As	Low Sc, Cu
Number of observations	153	428	694
Number with echo	75	317	352
Percentage detected	49	74	51

Notes.—(i) A few cases of cumulus fractus were included with cumulus humilis if humilis was the main cloud present but only fractus was overhead at the time.

(ii) Nimbostratus has been excluded from (*b*) because although it is by definition a middle-level cloud it usually extends down to quite low levels. In any case because of the rather small number of occurrences, its inclusion as medium cloud would only have raised the detection level from 74 to 76 per cent.

Detection ranges from 100 per cent for nimbostratus and cumulus congestus (and this would undoubtedly have applied also to cumulonimbus if any had passed overhead when the equipment was in operation, since this is essentially a precipitating cloud) to almost complete failure to detect cumulus humilis and cirrocumulus. The detection of the three types of cumulus shows a reasonable gradation, from 6 per cent for cumulus humilis to 57 per cent for cumulus mediocris and to 100 per cent for cumulus congestus. It is interesting that cirrostratus (91 per cent) is more readily detected than altostratus (83 per cent), and that both altostratus and altocumulus (68 per cent) are more readily detected than stratocumulus (62 per cent), despite the fact that the height of the lower cloud in each case should have aided detection. Some of the reasons for the trends shown by these figures may become apparent when the fine structure of these echoes and the evidence of particle size within them are described.

In Table I(*b*) the same observations are grouped as clouds at high, medium and low levels. It assumes that the individual cloud types were examined in proportion to their true frequency of occurrence. This seems preferable to an

analysis giving equal weight to each cloud type regardless of frequency. It shows about 50 per cent detection of high cloud and of low cloud, and about 75 per cent detection of medium cloud.

Evidence for the occurrence of precipitation in the observed echoes.—Table I has not taken any account of the presence or absence of precipitation in the clouds, though this significantly affects the appearance and intensity of the echoes received. The very narrow beam (8 minutes of arc in width) and short pulse (0.2 microseconds giving a discrimination of 30 m in range) were of great value in the examination of these effects, often revealing a fine structure of fallstreaks where with a broader beam one would have inferred a structureless echo.

The occurrence of significant fallstreaks within the echoes, whether or not they were reaching the ground, has been taken as a criterion of the presence of precipitation (Plate II). This can probably be justified, for Findeisen[8] has shown that a water droplet of diameter 20 μ in an environment with relative humidity of 90 per cent can fall only 3.3 cm before evaporating completely, a 200-μ droplet can fall 150 m, but a 2-mm raindrop could fall 40 km. Thus it seems likely that if fallstreaks are recorded which extend through at least 1 km in height, droplets of diameter at least 200 μ or large ice crystals of comparable fall speed are present in them. An alternative criterion was a report of rain, snow, or drizzle at the ground, and cases of 'a few spots of rain in the wind' were included. These minimum criteria are reasonably closely related because 200 μ is about the lower size limit for drizzle.

The results of this analysis are given in Table II where the third line of figures in both (*a*) and (*b*) gives percentages of echoes of each cloud type which gave evidence of precipitation (as defined above). It will be seen that 88 per cent and 94 per cent of echoes from altostratus and nimbostratus respectively showed precipitation effects. This is reasonable since these are by definition precipitating clouds, but surprisingly 50 per cent of cirrus echoes and 83 per cent of cirrostratus echoes contained fallstreaks. This suggests that cirrostratus should be classed with altostratus as essentially a precipitating cloud. Perhaps the most interesting result is the 68 per cent of altocumulus echoes showing fallstreak effects compared with 27 per cent of stratocumulus echoes, despite the shorter ranges at which the latter were measured. Overall, the percentage of echoes from high cloud with evidence of precipitation is much greater than the percentage from low cloud (Table II(*b*), line 3). This suggests greater efficiency of particle growth in the ice phase.

A calculation has been made to determine what proportion of non-precipitating cloud of each type was detected when clouds with evidence of precipitation were excluded (Table II(*b*) line 4). On this basis 40 per cent of non-precipitating low clouds were detected, 39 per cent of medium and 26 per cent of high clouds—substantially lower figures than those in Table I. To throw further light on these figures, levels of detection (similar to lines 3 and 4 in Table II(*b*)) were computed for two levels of sensitivity of the radar—at high sensitivity as already given in Table II and at a sensitivity lower on average by 6 dB. The effect will be described in terms of an increase of sensitivity of 6 dB; in the case of low cloud this was to increase substantially the detection of non-precipitating cloud (from 19 to 40 per cent), and to decrease the proportion of echoes containing evidence of precipitation (from 45 to 35 per cent). The effects on

TABLE II—STATISTICS OF THE OCCURRENCE OF PRECIPITATION IN CLOUDS AND OF DETECTION OF NON-PRECIPITATING CLOUD, (*a*) FOR INDIVIDUAL CLOUD TYPES AND (*b*) GROUPED AS HIGH, MEDIUM AND LOW CLOUDS

(*a*) Cloud type	Ci	Cs	Ac	As	Ns	Sc	Cu hum	Cu med	Cu con
Number of observations	121	32	250	178	34	286	149	219	40
Number containing evidence of precipitation	23	24	115	130	32	48	0	47	29
Percentage of echoes with evidence of precipitation	50	83	68	88	94	27	(0)	38	73
Percentage detection of non-precipitating cloud only	23	(63)	40	38	(100)	55	6	45	(100)

(*b*) Cloud types	High Ci, Cs	Medium Ac, As	Low Sc, Cu
Number of observations	153	428	694
Number containing evidence of precipitation	47	245	124
Percentage of echoes with evidence of precipitation	63	77	35
Percentage detection of non-precipitating cloud only	26	39	40

Note.—Percentages are enclosed in brackets if based on fewer than 20 observations.

medium and high cloud were similar to each other but differed significantly from the effects on low cloud. In both cases the proportion of echoes containing evidence of precipitation increased (from 63 to 77 per cent for medium cloud, and from 53 to 63 per cent for high cloud), but the detection of non-precipitating cloud remained almost unchanged (a decrease from 43 to 39 per cent for medium cloud, an increase from 24 to 26 per cent for high cloud). A possible explanation of these figures is that all precipitating low clouds had already been detected at the lower sensitivity, so that improved performance resulted in strengthened echoes plus many previously undetected non-precipitating echoes; but that not all the precipitating medium and high cloud had been detected at the lower sensitivity, or had not been recognized as such (the larger pulse-volume at high levels would have contributed to this). The main effect of improved performance could then have been to reveal fallstreaks in echoes previously classed as non-precipitating. If this explanation is correct a further increase in sensitivity might reveal an even higher proportion of precipitating high and medium clouds. The figures given at line 4 of Table II(*b*) for high and medium clouds may therefore be over-estimates. In the case of low cloud however the increase in numbers of weak echoes at high sensitivity was very obvious, particularly with stratocumulus and cumulus mediocris. They are seen to have a distinctive appearance, with well-defined tops but weaker and ill-defined bases often merging imperceptibly into background noise. They are thought to be the true detection of non-precipitating clouds.

Comparison with measured cloud droplet spectra.—The plausibility of the detection of non-precipitating clouds at high radar-sensitivity has been tested by comparison with droplet spectra measured from aircraft in cumulus clouds by Durbin.[6] He analysed about 150 cloud droplet samples obtained by a magnesium oxide slide technique in 10 cumulus clouds ranging from 250 m to more than 2 km in vertical depth. All samples were taken at heights below the 0° C level. A mean spectrum has been taken for each of the 10 clouds, since there was little evidence in them of any systematic variation of droplet

spectrum with height, or with successive penetrations at a single height, and the echo intensity to be expected from them at a fixed range of 2 km, equal to the mean sampling height, and at the best sensitivity of the radar has been computed. The values are given in Table III, arranged in order of increasing echo intensity, positive values being above noise, negative values below noise. It is seen that 2 of the clouds would not be detected, 2 are marginal (less than 3 dB above noise), and the remaining 6 should all be detected. Also given are the reported vertical depths of the clouds; the maximum droplet diameters recorded in them; and the droplet sizes making the largest contribution to echo intensity per unit size range—these last show good correlation with echo intensity. It is of particular interest that cumulus numbers 1 and 7 would have been detected by the 8.6-mm radar by virtue merely of the water droplets 30 μ or less in diameter contained in them.

TABLE III—RADAR SIGNAL INTENSITY TO BE EXPECTED FROM EACH OF DURBIN'S 10 CUMULUS CLOUDS, COMPUTED FOR A RANGE OF 2 KILOMETRES

Durbin's cloud number	4	3	2	8	7	1	5	6	10	9
Echo intensity (decibels)	−10	−5½	+1½	+2½	+5	+9	+9½	+15	+22½	+26½
Depth of cloud (metres)	600	230	2130	760	1170	1870	690	290	1510	1520
Maximum droplet diameter detected (microns)	20	60	30	40	60	40	60	85	120	120
Droplet diameter contributing maximum echo (microns)	10	15	15–20	15–40	20–30	20–30	30–60	60–85	60–85	60–100

Durbin's cumulus distributions are approximately exponential, as had been found in cloud droplet distributions by Best,[7] i.e. roughly straight lines on a logarithmic plot of concentration. Cumulus numbers 3 and 4, which it was found would not be detected, have extremely small concentrations of 20-μ diameter droplets and steeply sloped distributions typical of fair weather cumulus. The Malvern radar would have needed to be 10 to 15 dB more sensitive to have detected them. Cumulus numbers 9 and 10 on the other hand have concentrations of 10-μ droplets smaller by a factor of about five than the fair weather cumulus, and a shallow slope extending to much larger droplet sizes, features which Weickmann and aufm Kampe[8] have found in cumulus congestus. The remainder are intermediate in slope and probably correspond roughly to cumulus mediocris. Four out of 6 would have been detected. These figures are in reasonable agreement with the detection of cumulus humilis, mediocris and congestus reported in Table I.

Echo intensities were also computed for the droplet spectra measured in layer clouds by Singleton and Smith.[9] The values are given in Table IV. Even their shallow layer clouds should be detected with the 8.6-mm radar, and the echo intensities are in sequence both with layer thickness and with the droplet sizes (per unit size range) contributing most strongly to the echo intensity, as was found for the cumulus spectra.

TABLE IV—RADAR SIGNAL INTENSITY TO BE EXPECTED FROM SINGLETON AND SMITH'S LAYER CLOUDS

Layer thickness (metres)	200–300	600	2000–2300
Echo intensity (decibels)	+12½	+16½	+30
Maximum droplet diameter detected (microns)	70	70	140
Droplet diameter contributing maximum echo (microns)	35–50	≥70	70–110

Effects of attenuation.—The echo intensities calculated for cumulus and layer clouds are those resulting from their cloud droplet content alone, since particles of precipitation size are outside the range of measurement of the magnesium oxide slide technique. Precipitation was in fact noted on the aircraft windscreen on some of the traverses through Durbin's cumulus numbers 9 and 10, and light rain was reported at the ground from the deepest layer clouds studied by Singleton and Smith. Precipitation within the pulse-volume will increase the echo intensity, but counteracting and possibly even greatly exceeding this will be the effect at millimetric wavelengths of attenuation by intervening precipitation. Absorption of energy by precipitation along the path of the beam will reduce echo intensities, and may prevent recording of the full vertical extent of cloud and precipitation, quite apart from the normal loss with increasing range of target. The absorption occurs on both outward and return paths. Robinson[3] found experimentally that at 8.6-mm wavelength, rain attenuation is given approximately by $0.26R$ dB/km on a one-way path, where R is the rainfall rate in millimetres per hour. Attenuation by dry snow and ice crystals is negligible in comparison, but the attenuation by wet snow is quite high. Robinson, in one series of measurements in wet snow, found an attenuation two and a half times as great as in rainfall of equivalent rate.

One or two calculations of attenuation with a vertically-pointing 8.6-mm radar in typical rains will make its importance clear:

Example 1—In steady warm front rain of 2 mm/h with the 0°C level at 3 km, the attenuation up to the base of the melting layer would be about 3 dB. Attenuation through the melting layer should not add more than 0.6 dB, since the melting region is seldom more than 0.2 km deep, and attenuation in the snow above would be small, so that the total attenuation should not exceed 4 dB. This would probably not affect observation at lower levels, but might lose some of the snow echo otherwise detectable at high levels.

Example 2—In severe thunderstorms rainfall rates exceeding 50 mm/h over horizontal distances exceeding the beam width and extending through depths of 5 km or more would not be uncommon in this country. The attenuation through the first 3 km of this would be about 80 dB, sufficient to render undetectable even the heaviest precipitation at this and greater ranges, let alone cloud droplet distributions. Thus a grossly distorted height–time pattern can be expected in active thunderstorms. In lower latitudes this would be a frequent occurrence.

There are several other causes of loss at 8.6-mm wavelength, such as the absorption by cloud water droplets, by ice cloud particles, by water vapour and by other atmospheric gases. In addition there may be absorption by the skin of water on the aerial surface in heavy rain, loss due to precipitation particles comparable in size with the wavelength (for which the usual theory of radar back scattering does not strictly apply), and, at very short ranges only, the paralysis of the radar receiver while it is protected from the transmitted power-pulse. The combined effect of all these however is usually much smaller than the effect of rain attenuation at this wavelength. It is primarily rain attenuation which restricts the 8.6-mm weather radar to a vertically-pointing role.

Comparison with the work of others.—Some other evaluations of millimetric weather radars have been made, notably by Plank, Atlas and Paulsen[10] at 12.5-mm wavelength in Massachusetts, and by Wilk[11] at 8.6 mm

in Illinois. From the equipment parameters given in their papers it was calculated that, allowing for the longer wavelength, Plank's radar was about 7 dB less sensitive but that Wilk's radar could have been as much as 11 dB more sensitive than the Malvern equipment. This high performance was mainly due to the longer pulse employed and to the use of separate aerials for transmission and reception which allowed a lower noise level and smaller waveguide losses. With these values in mind it is of interest to compare their results for the detection of high, medium and low clouds with the ones reported in this paper (Table V). The figures follow the trend of the radar sensitivities, with the highest levels of detection reported by Wilk and the lowest by Plank *et alii*, but are nevertheless in broad agreement, despite these instrumental differences. The two values which differ most are the 87 per cent detection of low cloud by Wilk compared with the 51 per cent in the present analysis. It was found that there was a substantial difference in make up of the two sets of observations. Fifty-six per cent of the 694 low-cloud observations considered in this paper were cumulus clouds compared with only 7 per cent of Wilk's total of 269 low-cloud data. The 56 per cent probably weights the cumulus cloud too heavily (in particular the cumulus humilis which comprised 36 per cent of the cumulus clouds recorded) and the observation of fewer cumulus would have the effect of raising the overall level of detection. On the other hand, Wilk's cumulus clouds comprising only 7 per cent carry too little weight and his low-cloud detection of 87 per cent would undoubtedly have been less if cumulus clouds had been more strongly represented. For a high power 8.6-mm radar therefore, a low-cloud detection in the region of 60 to 80 per cent seems likely, depending on radar sensitivity.

TABLE V—COMPARISON OF ECHO DETECTION OF HIGH, MEDIUM AND LOW CLOUD WITH MILLIMETRIC RADARS IN AMERICA AND ENGLAND

Author	High cloud	Medium cloud *percentage detection*	Low cloud
Plank *et alii*	28	52	55
Harper	49	74	51
Wilk	54	75	87

Some sacrifice of sensitivity was necessary in the Malvern radar in order to achieve high definition: in fact its pulse-volume is 16 times smaller than Plank's and 85 times smaller than Wilk's. It is this which enabled assessment of the occurrence of non-precipitating as distinct from precipitating cloud. Plank *et alii* and Wilk did not attempt it perhaps because of poorer definition.

Conclusions.—Radar of 8.6-mm wavelength has the valuable ability to penetrate low-cloud layers and to detect a reasonable proportion of medium- and high-cloud systems, and this might in some circumstances be of overriding operational importance. However, the levels of detection found for high-sensitivity 8.6-mm radar, namely about 50 per cent of high cloud, 75 per cent of medium cloud and at best 60 to 80 per cent of low cloud, do not seem good enough to warrant its widespread operational use as a forecasting aid. It would not be possible to say with certainty from radar evidence alone that a particular aircraft flight level was clear of cloud.

These levels of detection might be acceptable if 8.6-mm radar could measure the heights of cloud bases and tops reliably, but evidence from the Malvern radar suggests that this is not often the case. The weak echoes from some shallow low clouds have clear-cut tops, and these, it is confidently thought, are also the

cloud tops and can be measured accurately, but the tops of echoes from medium and high cloud are rarely clear cut—an increase of sensitivity often reveals weak echo at a higher level. In addition, the radar evidence is that a large proportion of medium and high clouds contain embedded fallstreaks, giving a false indication of cloud base, so that there is uncertainty whether any of the echoes recorded at great heights represent true cloud-base measurement. Many of the echoes from low clouds certainly seem to be true cloud detection but, where these are detected at an intensity level only a few decibels above noise, there are grounds for thinking that the echo base does not coincide with the cloud base. The observations consistently suggest that the echo base is higher. A likely explanation is that the droplets in the base of the cloud though present in high concentrations are not detected because of their small size, but that higher in the cloud the droplets are larger and become detectable. Further evidence of the unreliability of 8.6-mm radar as an indicator of cloud base and top is that evidence of multiple-layered medium clouds was rarely seen, though it is reasonable to think that their occurrence cannot have been infrequent.

Nevertheless 8.6-mm radar often gives a good general indication of cloud structure, and shows that frequently precipitation is occurring aloft but is not reaching the ground. The frequent complexity of fallstreak patterns can give a fascinating indication of the variation of wind with height.

It would be of special importance if 8.6-mm radar could measure fog top. In some recent measurements with the Malvern radar, Harrold (unpublished) has recorded weak echoes from some denser water fogs, but has been unable to define the fog top. Other quite moderate fogs were not detected. A substantial increase in radar sensitivity, perhaps by as much as 20 dB, would probably be needed to improve significantly the levels of detection of cloud and fog. Technical advances, perhaps making use of shorter millimetric wavelengths, may make this possible in the future, but would not overcome pattern distortion caused by attenuation in heavy rain, a fault to which all millimetric radars are prone.

Acknowledgements.—The author is indebted to the Chief Scientist, Ministry of Aviation for the opportunity to evaluate the 8.6-mm radar, and wishes to thank Mr. J. R. Probert-Jones, now on the staff of Imperial College, London, Mr. H. W. Bahns of the Royal Radar Establishment, Mr. S. R. Smith of the Meteorological Research Unit at Malvern for the present high state of efficiency of the 8.6-mm radar and other staff of the Unit for their long hours of observation and analysis.

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SYMPOSIUM ON THE RESEARCH AND DEVELOPMENT ASPECTS OF LONG-RANGE WEATHER FORECASTING

A symposium was held at Boulder, Colorado, under the joint sponsorship of the World Meteorological Organization and the International Union of Geodesy and Geophysics from 29 June to 4 July 1964, the purpose of which was to discuss the scientific basis for long-range weather forecasting. It was attended not only by meteorologists directly concerned with the preparation of long-range forecasts, but also by others engaged in fundamental studies of the general circulation of the atmosphere.

Papers were presented which described the statistical approach to long-range forecasting as applied in India, Germany, Japan, Sweden, Poland, and the U.S.A., but there seemed to be little general expectation that any substantial advance would come from the development of these methods. Even the refined method of 'empirical orthogonal functions' applied by Gilman to forecasting by correlation methods gave steadily deteriorating results when applied to independent data.

Several papers discussed the factors external to the atmosphere which might be responsible for long-term weather anomalies. Professor Willett (Massachusetts Institute of Technology) stressed the role of variations of solar radiation particularly in relation to 22-and 80-year cycles, but generally there was more emphasis on the part played by sea surface temperature, various aspects being discussed in papers by J. Namias, J. Bjerknes, J. S. Sawyer and H. Flohn.

The most encouraging session of the symposium was that devoted to numerical studies of the general circulation. Experiments in the U.S.A. in computing the large-scale behaviour of the atmosphere were reported by J. Smagorinsky, J. Adem, Y. Mintz and C. Leith. Although the calculations were made on a variety of different assumptions, all showed that important features of the general circulation could be closely simulated by numerical calculation. Studies of energy exchanges throughout the northern hemisphere by A. Wiin-Nielsen (U.S.A) and T. Murakami (Japan) confirm several important deductions from the numerical models of the atmosphere.

In the discussions which followed the presentation of papers there appeared to be a general agreement that the numerical studies of the general circulation could contribute much to establishing a firmer basis than now available for long-range forecasting. Although direct numerical forecasting beyond the first few days is not yet possible, it was generally expected that calculations from the current state of the atmosphere would ultimately be able to give useful guidance over a period of 2 to 4 weeks. Parallel calculations based on slightly different initial data would however be needed to establish the degree of predictability, and the range of variation to be expected. It also seemed to be

generally accepted that for periods of a month or more allowance would have to be made for variations in some factors external to the atmosphere—sea temperature, snow cover, evaporation from vegetation, etc.

It was also recognized that until numerical dynamical methods have been developed considerably further, empirical studies of the large-scale atmospheric circulation in relation to sea temperature, snow cover and other factors can play a useful part in aiding the long-range forecaster.

The meetings were arranged by Dr. P. D. Thompson of the recently formed National Center for Atmospheric Research in the U.S.A. and took place on the campus of the University of Colorado. The excellent arrangements both inside and outside the meetings aided materially the valuable exchanges of ideas which went on at the symposium.

J. S. SAWYER

REVIEWS

Cloud physics edited by A. Kh. Khrgian. 9½ in × 6½ in, p. viii + 392, *illus.*. (translated from the Russian by the Israel Program for Scientific Translation, Jerusalem). Oldbourne Press, 121 Fleet Street, London, E.C.4, 1964. Price: £6.

This book is a translation of a Russian book published in 1961 and represents the joint work of a number of Soviet scientists. It is unique among textbooks on this topic in dealing with the large-scale properties of clouds as well as with the microphysics of the formation of cloudy air. It is to be welcomed therefore as a book containing a wealth of practical information of value to the day-to-day practising meteorologist as well as to the research engineer or physicist. The authors have ranged widely in their reading and there is ample recognition of work done outside their own country as well as a useful summary of their own, based primarily on extensive flying by research aircraft. The bibliography contains reference to 254 publications in Russian, including Mason's *The physics of clouds*, and a further 378 in other languages. By and large the translation into American has been well done, but there are one or two instances where a too literal translation is misleading; thus it needs to be remembered that in talking about "low" and "high" cumulus clouds the authors intended the adjectives to refer to the vertical extent of the clouds and not to the height of the cloud base—"small" and "large" would have been better. The reviewer also puzzled somewhat over "frontal downpour clouds" before realizing that "downpour" meant "shower." The proof-reading has not been so well done and there are several small errors, perhaps the most serious of which to a casual reader would be the heading of the first column of Tables 23, 24, 25 as g/cm^3 when g/m^3 is intended.

The first chapter discusses the basic microphysics of condensation of water vapour on nuclei and their subsequent growth by diffusion and coalescence. This is followed by discussion of sublimation, the freezing of water droplets, and freezing nuclei. It is now familiar work and is dealt with more exhaustively in Mason's book.

The second chapter deals with the microstructure of clouds in terms of average drop-size distributions and water content and it would be better if the limitations of the measuring instruments were clearly expressed here rather than deferred until the eleventh and last chapter of the book.

After a short third chapter on the classification of clouds the next five chapters, which form the most valuable part of the book, discuss in some detail the structure and formation of cumulus, stratiform, altostratus and altocumulus, frontal and cirrus clouds. In the chapter on cumulus there is extensive reference to the American Thunderstorm Project and a reference to the aircraft "Meteor" which, although attributed to the U.S.A., was undoubtedly engaged in our own smaller thunderstorm investigation with pilots and observers from the Royal Aircraft Establishment. The section in this chapter on graupel and hail is disappointingly brief with no theories of formation and very little observational material.

A chapter follows on aircraft icing with a detailed discussion of the efficiency of catch of water droplets by cylinders and aerofoils. In the succeeding chapter on artificial stimulation of cloud and fog the accent is more on the dissipation of cloud and fog than on rain-making and it is clear that the claims for success in dissipation are more soundly based than are those elsewhere for enhancement of rain.

The concluding chapter describes various instruments for the capture of droplets and crystals and for the measurement of cloud water content from aircraft. It is interesting, but misleading, to read that the Meteorological Research Flight at Farnborough has four Hastings aircraft (only one) and the tropopause would need to be unusually low for this aircraft to explore the low stratosphere!

The book represents a good attempt to link the microphysics with the large-scale processes of cloud formation and dissolution and is a useful addition to meteorological literature.

R. F. JONES

The problem of the professional training of meteorological personnel of all grades in the less-developed countries by J. Van Mieghem. (World Meteorological Organization Tech. Note No. 50.) 11 in × 8¼ in, pp. x + 76, Secretariat of the World Meteorological Organization (WMO), Geneva, Switzerland, 1963. Price: Sw.F.4.

One of the primary aims of WMO is to encourage training in meteorology and to assist in co-ordinating the international aspects of such training.

With the emergence of several newly independent States during the last decade, WMO has given increasing attention to the training needs of the less-developed countries. In 1961 Professor Van Mieghem, who was Professor of Meteorology in the University of Brussels, and is now Director of the Meteorological Institute in Brussels, was engaged by the Organization, as a consultant, to assist in this task. He prepared three reports, of which this Technical Note is one.

The report underlines the essential requirements that all meteorological personnel, at the beginning of their careers, should be given a thorough training in the basic elements of meteorology. The level of such training will vary considerably from one grade to another, and assumes a prerequisite minimum knowledge of mathematics and physics appropriate to the grade.

It is recognized that there is a lack of uniformity in the grades of meteorological personnel employed by different national meteorological services. The report considers four classes, ranging from university graduates in mathematics

or physics (Class I) who would be engaged in highly scientific work, to Class IV personnel whose duties would mainly be concerned with the making and plotting of synoptic observations. Comprehensive syllabuses for each of these classes are given in detail in Annexes I to IV.

The establishment of national meteorological schools for the training of Class IV personnel is advocated, and of international regional centres for Class II and Class III personnel. The training of Class I personnel is considered to be a task for the Universities or for major meteorological schools of university level.

Attention is drawn to the need for instructional personnel to be both highly qualified and highly experienced, and for them to receive instruction in teaching methods.

Refresher courses and seminars are recommended to enable operational staff to keep abreast of new developments in the science.

Annexes V to VII summarize the comments on the report made by the Executive Committee of WMO, by Members of WMO, and by the Presidents of WMO Technical Commissions.

In publishing the report, the Executive Committee of WMO stresses that it should be considered as advisory material which would be useful to countries establishing or expanding their training facilities. W. R. GALLOWAY

OBITUARY

Dr. M. Doporto

We regret to record the death of Dr. M. Doporto, Director of the Irish Meteorological Service for the past 16 years. Dr. Doporto died suddenly in Dublin on 8 September, at the age of 62.

Dr. Doporto was well known to meteorologists in this country and elsewhere. A Spaniard by birth, he joined the Spanish Meteorological Service in 1921 and became officer-in-charge of the Weather Forecast Centre at Barcelona. The upheavals of the Civil War compelled him to leave his country, and in 1939 he joined the newly-formed Irish Meteorological Service. In 1948 he succeeded Mr. A. H. Nagle as Director.

Dr. Doporto was a scholar of distinction whose work lay mainly in dynamical meteorology. He dealt with the hydrodynamical equations of motion and the cellular structure of atmospheric circulations and in 1943 predicted the existence of a second isopycnic layer near 25 km, which was subsequently verified.

He was a member of the Board of Dublin Institute for Advanced Studies and maintained a lively interest in his subject to the end.

Dr. Doporto was a prominent figure in the world of international science and at the time of his death was Chairman of the Finance Committee of the International Union of Geodesy and Geophysics. He was a frequent and sometimes highly critical speaker at the Congresses of the World Meteorological Organization, of which he may rightly be regarded as one of the 'founding fathers.'

As one who often debated with Dr. Doporto in the business meetings of WMO, I shall miss him greatly. Although he always spoke his mind frankly and pressed his points with fervour, he was invariably courteous and outside the

meeting room was the most friendly and entertaining of colleagues. He was a man who was regarded with respect and affection by all who knew him, and the meetings in Geneva will never be quite the same without him.

Dr. Doporto leaves a widow and three sons, to whom we send our deepest sympathy.

O. G. SUTTON

LETTER TO THE EDITOR

Solar halo

Unusual solar haloes were seen at Lerwick Observatory on the morning of Sunday, 14 June 1964. The phenomena were remarkable both on account of the brilliance of the unusual phenomena that were visible as well as the complete absence of some of the more common halo phenomena.

The halo system was first seen at 0950 Universal Time (UT): all except the 22° halo had disappeared by 1020 UT. The elevation of the sun was 47° at 1000 UT.

The accompanying sketch (Figure 1) shows what was seen at the Observatory by the observer Mr. L. S. Leslie. The common 22° halo was bright except in the east where it was faintly seen inside a very bright part-circumscribing elliptical halo (*Observer's handbook*[1]) which extended from a point level with the sun on the east side to the highest point of the 22° halo, with which it made contact, and thence partly over to the west side. Another member of the staff, Mr. J. Cubin, from a point 2 km away, saw the whole of this circumscribing elliptical halo and estimated the semi-major axis to be 26°. The lower contact arc was very bright,

FIGURE 1—DIAGRAMMATIC SKETCH OF THE SOLAR HALO PHENOMENA SEEN AT LERWICK ON 14 JUNE 1963

a 22° halo round the sun S,
b,c upper and lower arcs of contact,
d,d infralateral tangent arcs of the 46° halo.

The pecked lines joining b and c show how another observer saw them joined together to form a circumscribing halo which was approximately elliptical with a semi-major axis estimated as 26°.

and appeared almost straight—presumably the 22° halo, the elliptical halo and the lower arc of contact (which is concave downwards) were superimposed and gave the appearance of a straight arc.

In addition there were two very bright and almost straight streaks below the sun and on either side, as shown in Figure 1. These are not mentioned in the *Observer's handbook*, but the *Compendium of meteorology*[2] describes these as the infralateral tangent arcs of the 46° halo (which was not visible at all).

Except at the lower arc of contact, which was mainly red and yellow, all these arcs and haloes showed almost the complete range of spectral colours; certainly from red to green and with an impression of blue. There were no mock suns, sun pillars, 46° halo or any white (reflection) halo. During the Aberdeen meeting of the Royal Meteorological Society on 29–30 June there was some discussion on what practical use could be made of observations of solar halo phenomena. The general opinion was that unusual haloes occurred because unusual atmospheric conditions allowed unusual ice crystal formation to take place.

Meteorological Office, The Observatory, Lerwick. R. A. HAMILTON

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1. London, Meteorological Office. Observer's handbook. London, HMSO, 1956, p. 130.
2. Boston, American Meteorological Society. Compendium of meteorology. Boston, Mass., 1951, p. 69.

NOTES AND NEWS

Retirement of Michael J. Morley

When the Republic of Ireland came into being in 1922 the Meteorological Office continued to administer the Irish meteorological stations and especially to maintain the Valentia Geophysical Observatory at Cahirciveen, Co. Kerry. Not until 1936 was the Irish Meteorological Service formed, and it was a few years after that before sufficient staff had been recruited to take over completely.

Michael Morley was among the assets taken over. A native of Cahirciveen, he had started work at Valentia Observatory under L. H. G. Dines in 1915. Twenty-four years later he helped to found Shannon Airport and was then transferred to Dublin Airport. It is in his 25th year of service there that he has reached the age of retirement.

His flair was, and is, instruments. Many, many men have learned from him the art of humouring temperamental anemographs and sulky ceilometers. Those men, whether working with him, or under him, or over him, have all imbibed more than mere technique. They have learned that even in the routine of airport meteorology the job can be a vocation. The Irish Meteorological Service is still young, but through Michael Morley it is linked to the old tradition established by such dedicated men as FitzRoy, Scott, Dines and Shaw.

We join all his past and present colleagues in wishing him a long and happy retirement.

F.E.D.

THE METEOROLOGICAL MAGAZINE

VOL. 93 NO. 1108 NOVEMBER 1964

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Printed in England by S. Cockburn & Son Ltd., Ossett, Yorks. and published by

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Three shillings monthly **Annual subscription 39s. including postage**

S.O. Code No. 40-43-64-11